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AND
TRANSPORTATION SYSTEMS

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Disclaimer

The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors.

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SUMMARY

This report represents a synthesis of current information on the energy-related aspects of transportation systems. It is intended to be a source of data and a textbook for engineers, planners and others responsible for performing energy analyses and preparing environmental impact statements.

The text presents the following:

1) An introduction to the current use of energy in transportation, which is primarily in the form of petroleum fuels, and predictions indicating the rapid depletion of sources by the end of the 20th century; and a discussion of the method followed by the researchers, which was primarily a far-reaching literature search and evaluation of existing information.

2) A discussion of the basic considerations relating to the subject, including: the need to consider not only the fuel (direct energy) used by vehicles, but the remaining (indirect) energy required to manufacture and maintain the vehicles, as well as to construct and maintain necessary facilities such as roads, airports, peripheral equipment, pipeline pumps, etc.; the need to consider the actual service being rendered by a system or a vehicle, which is usually far below its theoretical potential; the need to consider the potential effects a project may have in the fuel/energy distribution of a geographic region; and other considerations.

3) Descriptions of the most important parameters affecting the rate of energy consumption of vehicles (such as engine type and fuel, weight, speed, altitude, and grade), depending on the particular transportation mode; and descriptions of the facility-related parameters (such as type and quantity of materials used, construction methods, practical useful lives, operation, and maintenance). Studies correlating construction/maintenance energy vs dollar expenditures are also discussed.

4) Recommended procedures for performing analyses of transportation energy consumption and comparing alternatives are discussed, along with a rational method of presentation of the results of an energy analysis.

5) An "Energy Factor Handbook" (Appendix A), containing substantial quantities of numerical data relating to energy associated with fuels, materials, vehicles, construction, operation, maintenance, dollar costs, etc. It is keyed to the source for the handbook (Appendix C).

CHAPTER ONE

INTRODUCTION

Background and Problem Statement

Every activity consumes some form of energy. Transportation in the twentieth century is directly consuming ever-increasing amounts of energy, approximately 96% of which is obtained from petroleum(1). Various estimates of domestic petroleum reserves and consumption rates indicate that these reserves will be depleted between the years 1993 and 2086(2). Also, the indirect consumption of energy for transportation system materials and processes competes with other important energy needs. It is anticipated that these needs will continue to grow more rapidly than the available energy supply.

These predictions point to the need for conservation and a shift to transportation technologies using alternative energy (fuel) sources. Conservation requires a reduction in the rate of energy consumption. Achievement of this result requires the careful selection and use of transportation facilities which provide the required service with minimum energy consumption.

Society, as represented by government and industry, has only recently recognized the potential impact of depleting petroleum fuels. Thus, transportation systems have developed without adequate study of their energy consumption characteristics. Studies of this nature have been conducted by a handful of farseeing individuals, and their work has acted as a nucleus for the subsequent research effort sponsored by government. It should be recognized that not much is known about transportation energy, and a large portion of the available data is based on informed estimates rather than scientific test.

Research Objectives and Approach

The objectives of this study were threefold. The first was to establish a list of "energy factors" for materials of construction, construction processes, maintenance processes, and operation of the system based on a synthesis of existing information. The second was to develop procedures for evaluating transportation systems in terms of relative energy use with respect to modal, spatial, and temporal alternatives both for planning and design using the energy factors established. The final objective was to develop a rational method for reporting the results of an energy use analysis.

The approach to the first objective involved conducting a far-reaching literature search, as well as in-house studies, to obtain and organize as much of the current knowledge on transportation-related energy as possible. Following the acquisition of available information, the material was reviewed, cross-referenced and compared. Where there were substantial differences in data for the same item, the authors exercised their prerogative of making the - often difficult - choice of which values to present. Finally, the selected data were organized for presentation.

For following this approach, an apology is due to the many authors whose material is incorporated in this report. The brevity of presentation has, of necessity, eliminated many of the amplifying remarks and caveats to be found in the source documents. The sources - keyed in the appendices to specific subjects - should be consulted for a broader understanding of the methods used by each author to develop his data and arrive at his conclusions.

Development of the procedures in the second objective was oriented toward assisting engineers, planners, and other professionals responsible for producing energy analyses. The purpose of the procedures would be to provide basic guidelines for comparison of alternative transportation facilities and projects and energy conservation measures based on their respective energy consumptions.

This orientation required procedures that could be applied without having to search through other references or having to possess an extensive knowledge of the energy field. It also required procedures sufficiently definitive to enable analyses ranging from project design to system alternatives.

Energy use had to be categorized in many ways: as being direct or indirect, in terms of transportation mode, in terms of vehicle operation mode, and in terms of materials and processes.

The approach to the reporting method was based on the uses that might be made of an energy analysis. In most cases, an energy analysis would serve as an additional element in the decision-making process and, in some cases, would be required as an input to an environmental impact statement. The latter application would probably be the most stringent and it was that application the approach addressed.

Conforming to the objectives and the research approach, the report is organized as a manual/handbook, and is intended as a basic text on the subject of energy and transportation systems. It includes a broad discussion of the subject, important points and theory for consideration, recommended methodology for preparation of energy comparisons in environmental impact reports and, in the appendices, includes comprehensive lists of energy factors and a glossary of terms.

Parallel and additional information on energy factors is included in "Energy Effects, Efficiencies, and Prospects for Various Modes of Transportation"(3).

General Transportation Energy Discussion

Every physical action requires the expenditure of energy. Primitive societies relied almost entirely on one form of solar energy for their needs - that which made plants grow for food directly or as food for game animals (biomass energy). As societies, through the genius of inventors, become technologically more complex, other forms of solar energy effects were used - wind for ships and windmills, falling water, and again, biomass, both for food and firewood. More recent technology, seeking new sources of energy, has added solar effects such as coal, oil, and gas to the list. Finally, in the twentieth century, additional solar sources (such as photovoltaic) as well as nonsolar energy sources (such as chemical and nuclear energy) have been developed.

Historically, technological advances have been followed by increased demand for energy. This fact, combined with a rising world population, has been increasing the rate of energy consumption at an accelerating pace, particularly in the developing countries. The result is that certain finite energy sources are being rapidly depleted. These sources are, primarily, petroleum and natural gas. The known or estimated reserves of petroleum, used as fuels and as raw materials for plastics, etc., are expected to be consumed in the late part of the 20th Century or the early part of the 21st Century, as indicated by the various predictions presented in Figure 1.

Population growth, along with technological advances and price, places a severe strain on the materials and energy requirements of a society. Recent estimates place the annual growth in world oil consumption over the next few years at 3.5%. Due to the sharp price increases since 1973, this is down from the 7% figure that prevailed between 1955 and 1973.

Petroleum fuels are of vital importance to transportation because they embody two qualities not shared with most other fuels: they provide, simultaneously, highly concentrated and portable energy. In comparison, electric batteries are portable, but their energy density, even in advanced concepts, cannot even approach that of gasoline; nuclear power is highly concentrated, but weight penalties for shielding, etc., severely limit its portability; other fuels, such as hydrogen, require large-volume, heavy pressure tanks (for compressed gas) or a continuous leakage rate to maintain supercold temperature (for liquid hydrogen). The potential of hydrogen fuel stored as iron-titanium hydride is also being studied in prototype vehicles. Fuels such as alcohol, derived from biomass, and synthetic fuels from coal are most likely to receive increasing attention because they share some of the attributes of petroleum fuels and would require a minimum investment in changes to fuel distribution systems and the internal combustion engine.

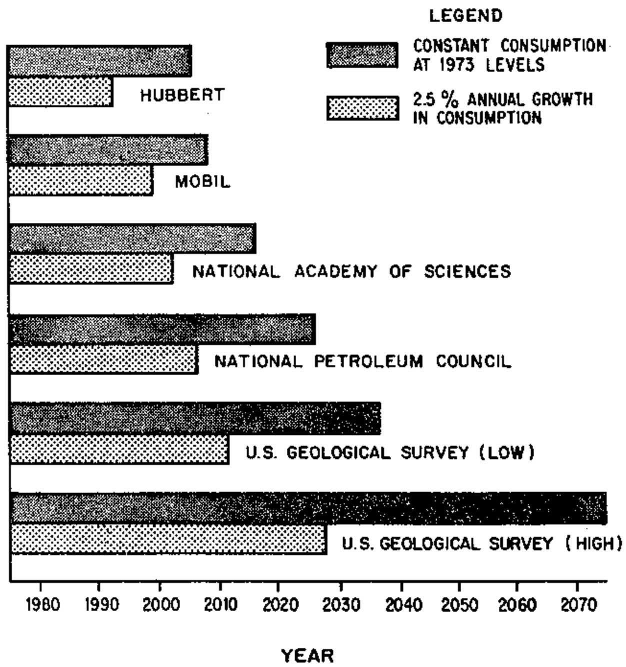

Fig. 1 Estimates of exhaustion date for domestic oil and natural gas liquids, assuming 35 percent imports.
Source: Ref. (2)

Under current technology, however, the advantages of petroleum fuels make them the overwhelming choice for providing the energy required in transportation. This fact is reflected in the estimate that 96% of energy used by transportation is derived from petroleum, and much of the remainder from natural gas(1).

Not only does transportation consume the most rapidly depleting form of energy; it also accounts for a significant portion of the over all energy consumption for all purposes. Recent estimates indicate that transportation fuel consumes 25% of the total national energy expenditure(4). When combined with indirect items such as vehicle manufacture, facility construction, maintenance, peripheral facilities, etc., the total transportation system consumes about 43% of the total expenditure, as shown in Figure 2.

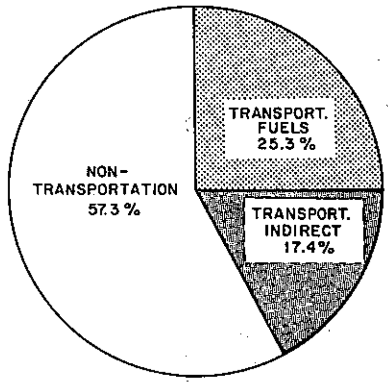

Fig. 2. Distribution of total U.S. energy consumption (1967).
Source: Loebl et al.(6).

A preeminent factor influencing transportation system development has been economics. From an energy standpoint, the choice of fuel for transportation - or for any other use, for that matter - was governed by the financial cost/benefit ratio inherent in any fuel-vehicle-service system. The effects of depletion were ignored, or regarded as inevitable, and short-term viewpoints were more attractive, especially in the face of low prices for raw petroleum.

Another factor that must be considered at this time is that the current transportation system is in existence and represents a tremendous investment by society, which is not willing to drastically change its life-styles.

Rising prices for petroleum and petrochemicals, and increasing concern over limited supplies, is forcing a review of priorities in decision-making on how and what type of energy should be consumed. Although new technologies are evolving, the emphasis on energy conservation is increasing. Modern transportation systems - evolving over the last century on an "abundant energy" basis - cannot be eliminated, nor can adequate substitutes be found in the short-term future. However, the fact that such systems were not designed with energy conservation as a primary criterion allows substantial improvement in their energy consumption characteristics. A mid-term conservation technique, for example, has been the requirement under U.S. Public Law 94-163, known as the Energy Policy and Conservation Act of 1975, that new private cars should travel an average of 27.5 miles per gallon of gasoline by 1985, as opposed to the prevailing rate of 14 to 15 miles per gallon in 1975, when the law was signed.

Long-term conservation techniques involve research in the field of transportation energy with the purpose of identifying exactly where the energy is being consumed. This research is followed by critical analysis and decisions on transportation-related projects, with emphasis on conservation, and research in the field of alternative modes of transportation that would provide more energy-efficient service. This research is just beginning to bear fruit, and the energy consumption by various modes of transportation is being identified (Fig. 3).

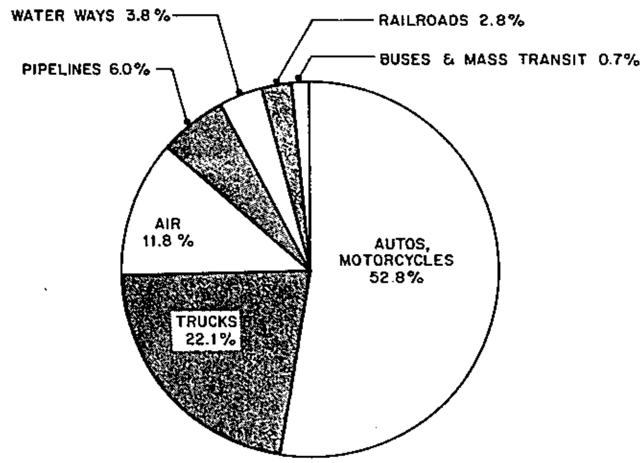

Fig. 3. Proportion of direct energy consumed, by transportation mode (1972).
Source: Pollard et al (5).

The real problem, however, is one inescapable fact: All indications are that natural petroleum fuels - the life blood of transportation as we know it - will become unavailable, in a practical sense, within the foreseeable future. Conservation will not alter that fact. As the supply of natural petroleum decreases, prices will increase and will probably lead to the use of synthetic fuels from tar sands, oil shale, and coal as supplements. Eventually, new technologies will have to be developed to provide for the world's ever-expanding energy needs. The true benefit of conservation is that it may buy time for the development of synthetic fuel and new energy source technologies, thus providing a more orderly transition to the future.

Decisions on transportation systems and related projects must be based on predictions of future effects these systems-projects may cause. These predictions are incorporated in environmental impact statements (EIS) or reports (EIR). Among other considerations, such as social and economic impacts, these reports must also address the impact of energy consumption, conservation, and other energy-related factors. Adequate data will permit informed decisions on energy vs economic trade-offs, similar to pollution vs economic trade-offs made in current practice.

Public Law 91-190, known as The National Environmental Policy Act of 1969 (NEPA), requires that an EIS be prepared for federally funded projects and submitted for approval. This Act also established the Council on Environmental Quality (CEQ), which in turn established guidelines for the contents of EIS's. One of the required subjects for discussion is covered by the phrase: "Any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented". Energy consumption, although not specifically mentioned, is irreversible and irretrievable and should be included under this guideline.

The U.S. Department of Transportation, recognizing the necessity for incorporating an energy discussion in an EIS, issued DOT Order 5610.15. This order requires a discussion of significant effects on either energy production or energy consumption.

The Federal Highway Administration (FHWA) includes a requirement for discussion of significant energy impacts in the Federal-Aid Highway Program Manual (FHPM). This requirement (FHPM 7-7-2) appears under the heading, "Natural, Ecological, or Scenic Resources Impacts."

Public Law 94-163, previously mentioned, places strong emphasis on energy conservation, and requires states to produce plans to that effect and submit them to Federal authorities. This law further augments the NEPA-CEQ requirements.

Agencies responsible for transportation systems must meet certain legal requirements. In the United States, transportation agencies must meet federal law and federal agency regulations, as well as comply with state and local laws and regulations.

Section 108 of Public Law 95-95, The Clean Air Act Amendments of 1977, requires assessment of the energy impact of various transportation control measures and strategies. Individual states (e.g., California) are beginning to require by statute that energy be addressed in environmental impact reports.

This report is intended to assist responsible agencies to comply with these existing regulations, as well as future ones, for the preparation of comprehensive and factual analyses of energy use due to proposed transportation projects.

CHAPTER TWO

FINDINGS

OBJECTIVES OF THE STUDY

This study has addressed itself to attainment of the following objectives:

1. Establishing a list of "energy factors" for materials of construction, construction processes, maintenance processes, and operation of the system based on a synthesis of existing information.
2. Developing procedures for evaluating transportation systems in terms of relative energy use with respect to modal, spatial, and temporal alternatives for both planning and design using the energy factors developed.
3. Developing a rational method for reporting the results of an energy use analysis.

BASIC CONSIDERATIONS

Energy Units

Transportation may be described as the act of moving an object from one location to another. To perform this act, certain impeding forces (gravity, friction, etc.) must be overcome. To overcome these forces and achieve the desired transportation, work must be performed, which requires the expenditure of energy. Energy is defined as the ability to do work. It is thus convenient to describe energy in terms of units of work. A typical unit of work, for example, is a foot-pound, and a substance - say a fuel - capable of producing one foot-pound of work may be said to contain one foot-pound of energy.

Energy is present in many forms, such as chemical, kinetic, nuclear, potential, and thermal. One of the most important forms related to transportation is thermal energy; i.e., the heat value contained in fuels used for propulsion of vehicles. Classical experiments have determined the correlation between thermal energy and mechanical energy (foot-pounds) and, in fact, the units for all forms of physical energy are convertible to each other.

Commonly used units of transportation-related energy are the British thermal unit (Btu) in the English System and the Joule in the International System of Units (SI). Still in considerable use is the kwh (kilowatt-hour), which usually describes electrical energy. The American Society for Testing and Materials (ASTM) recommends that the kwh units be avoided, and expects their use in electrical applications to be superseded by the megajoule(7).

These units of energy should be used in the technical calculations required in an energy study. In order to provide a common unit to which a layman can relate, and to facilitate comparisons between alternatives using different forms of energy, it is recommended that the final values obtained through analyses be converted to "equivalent barrels of crude oil" (see Appendix D).

Direct and Indirect Energy

Transportation-related energy is usually separated into two main categories:

"Direct," defined as the energy consumed in the actual propulsive effort of a vehicle, such as the thermal value of the fuel, or quantity of electricity used in the engine or motor.

"Indirect," defined, in the broadest terms, as all the remaining energy consumed to run a transportation system. Although the definition of direct energy is relatively simple, both in concept and in measurement, the concept of indirect energy requires some in-depth discussion:

Indirect energy may be divided into two broad subcategories: central energy use and peripheral energy change. Central energy use encompasses all the energy resources used indirectly in building and operating a transportation system. It addresses the fact that energy must be expended to create and support a transportation system; for example, mining and refining raw materials into useful products such as vehicles or roads, exploring for and refining oil into various fuels, constructing and maintaining dams, power plants, transmission lines, fuel distribution systems, train stations, airports, maintenance facilities, etc. Thus, central energy use includes all but the fuel used for propulsion in a transportation system. It may be argued that items such as lubricants or tires should come under the "direct" category, and, although this does have some merit, it makes no difference in the final analysis, as long as these items are included in either direct or indirect energy consumption.

Peripheral energy change recognizes energy resources that are not used in any manner by the system itself. Rather, it addresses the potential effect that a transportation system may have on energy use and availability in the area it serves. For example, a highway through an agricultural area preempts certain acreage that would otherwise be used in the production of crops to produce energy in the form of food or as raw fuel for biomass conversion plants; or a sizeable shift in population density, land use, or transportation patterns may be fostered, or induced, by a project, which will have an impact on the energy demand, supply, and distribution within a certain geographical area.

It is much simpler to define qualitatively the concept of direct and indirect energy consumption, than to obtain reliable numerical data. The energy content of fuels may be obtained in the laboratory from bomb calorimeter tests. Fuel consumption rates of vehicles, especially road vehicles, are constantly being measured by the Environmental Protection Agency (EPA) and other organizations. Thus, measurement of direct energy is relatively well documented, especially for roadway vehicles. However, measurement of indirect energy consumption is very complex and its study is still in its infancy, especially the subject of peripheral energy change.

The current state of the art requires that almost all data presented in this report be labeled as "approximate," or "estimates." Continuous repetition of these adjectives, however, would create a cumbersome and unmanageable document; their use has therefore been reduced to a minimum. The informed reader will appreciate the need for this, and make the appropriate allowances.

Considerations in an Analysis

The purpose of an energy analysis is, usually, to provide meaningful comparisons between alternatives, including the "do nothing" alternative. This requires careful consideration of the factors involved in analyzing the energy impacts of each alternative. The relative lack of specific data tends to promote simplification of portions of the analysis, and this may be proper, provided due attention has been paid to certain philosophical considerations, as discussed in the following.

1. Direct and indirect energy must both be considered, otherwise erroneous comparisons may result. A car cannot operate without a road, nor an aircraft without an airport... or even a ship without periodic dredging of channels. Even within the same mode, two alternatives may vary substantially as to their direct and indirect energy. For example, a roadway tunnel may cut the distance and grade traveled by vehicles, thus reducing direct energy consumption, but will probably require more indirect energy to construct, than a more circuitous route. This fact must be brought out by the analysis.

2. Transportation is portal to portal; i.e., the fact is that people and goods are transported from specific geographic locations to others, and not from airport to airport, or train station to train station. Energy analyses must consider the total transportation system (and energy use) required to transport, say, a commuter, from a specific address (his home) to another specific address (his place of work). This may involve several modes of transportation.

3. The difference between actual and potential transportation must be given careful consideration. Potential service of a vehicle would be the maximum rated capacity for passengers or cargo, and actual service is the real number it does carry. The implications of this concept are vital in comparisons between different transportation modes. For example, a commuter bus may be full in one direction, taking people to work or shopping, but may return nearly empty to complete the loop of its route. Its potential is there to carry a full passenger load on the return trip, but this is, practically speaking, impossible. Thus, although it consumes fuel for the complete loop, it actually provides transportation for fewer than the maximum rated passenger-miles. The same holds true for, say, a delivery truck, which leaves the warehouse full and returns empty. The ratio of actual service rendered vs potential service is called the "load factor" and must be used in connection with an energy analysis.

Load factors also hold for private vehicles, as exemplified by a passenger car rated for 6 seats and carrying only the driver having a load factor of 1/6, whereas motorcycles, usually considered as single-seaters in spite of the extra-long seat and foot pegs for a passenger, may actually be given a load factor of 2.0, when a passenger is carried.

4. Certain goods lend themselves naturally to specific modes of transportation. Perishable cargo lends itself to air transport, but iron ore is seldom shipped in this fashion. Natural gas and pipelines go together, but appliances are transported by rail and truck. Cargo density and fragility also become an important factor in determining which mode of transportation is practical. A commonly used unit of goods transport is the "ton-mile," depicting the movement of one ton of freight the distance of one mile, but it is important to specify the type of cargo, to avoid misleading generalizations about the relative efficiency of various transportation modes. For example, a supertanker may use less energy per ton-mile than a truck, but this would hold true for oil or bulk cargo, not for transporting eggs.

5. Other aspects of transportation service (such as time value, hours of available service, and the temporal and spatial availability of access and egress) are also important in the analysis of modal alternatives. Unless equivalent transportation service occurs in the alternatives, the analysis is less than rational.

6. Certain items may be used either as fuel or as structural material. Wood is an obvious example. In the case of roadway and airport construction, asphalt, a major constituent, falls in this category. Because, generally speaking, these materials are not "consumed" when used in construction, their inherent thermal energy is potentially available for future use, i.e., highways act as reservoirs of asphalt. It is important, however, to consider the practicality of extracting this material for further use. If this extraction is judged impractical, then the thermal energy of the material should be charged against the construction project. (The authors support the viewpoint that asphalt, once used on pavements, cannot be reclaimed practically for use as fuel.)

7. The ease with which materials lend themselves to recycling can be important in an energy analysis. Both portland cement concrete (PCC) and asphaltic concrete (AC) pavements can be recycled. Although both become aggregate during the process, much of the asphaltic binder in the AC can also be recycled by heating and fluxing whereas the portland cement in the PCC cannot. This property may be very important in an analysis of a pavement type.

The Technical Approach

An energy analysis, although containing many elements of art, does lend itself to the technical approach. This approach is based on due consideration of the physical laws of thermodynamics and on empirical data obtained by research and experimentation.

The first law of thermodynamics establishes the definite convertibility of mechanical work to and from energy, and the second law establishes the concept of entropy, in which energy, once expended, cannot be fully recovered. This leads to the concept of efficiency, which is a measure of the energy output of a process (say, an engine) vs the energy input required to run the process. For example, a typical petroleum-fueled electric power plant requires three units of energy input (in the form of fuel) for every one unit of energy it produces, the rest being lost mostly in the form of heat at the stack, and in mechanical and transmission losses. Such a system is said to have an efficiency of 0.33(8,9,18). The over-all efficiency of various systems plays an important part in the energy analysis.

The Process Approach

Empirical data provide estimates of the "energy worth" of items such as fuels; the energy consumed by vehicles; the energy required to produce various materials or finished products; the energy consumed in maintenance and repair of transportation facilities; and the actual "load factors" inherent in various transportation systems. These empirical values, or "energy factors," are in the process of being established and refined, and they incorporate various "reasonable assumptions." Typical approaches to data collection are, for example, obtaining statistics of throughput of a steel-producing plant, and the amount of energy consumed (in the form of fuel and/or electicity) to run the process. This would be followed with similar studies of ore-mining operations and transport, the end result being a figure for the total energy that went into producing a steel product. On a smaller scale, the energy inherent in, say, an automobile tire would be measured by obtaining statistics of throughput of a tire producing plant, along with the amount of energy consumed to run the process. This would be followed with similar studies of the energy required to grow natural rubber (or produce synthetic material) and to ship this raw material to the tire plant. Another process approach to measuring this energy would be obtaining the thermal energy of rubber, as reported by steam-producing plants that use old tires as fuel. This is followed by measurement of the amount of tread rubber worn off, to the point of replacement, and by investigating the percentage of tires that are retreaded and the energy associated with this process. The end result is a figure of energy consumed per mile driven. Tire wear values reported in Appendix A are based on the thermal energy approach, for which data were available. The manufacture energy of tires is not included, and thus could lead to erroneous values if the thermal energy is not substantially higher than the manufacture energy, thus "masking" its effect.

The inherent drawback of the process approach in the development of energy factors is that it requires considerable data collection and calculations, and that it is difficult to define an end-point to the study of the various input elements. Does one consider, for example, the energy consumed by workers commuting to the tire-making factory? This last problem has been mitigated through use of the techniques of "sensitivity analysis," discussed later in this chapter.

The Input-Output (I/O) Approach

A technique, developed for the field of economics, is available, which cross-relates all the goods and services required as input to the U.S. economy in order to produce another good or service. This I/O matrix does not deal directly with quantities of goods or services, but with their costs, in terms of dollars. The energy inherent in a product is presented in terms of the dollar costs of fuels bought or sold to create a dollar's worth of this product. Thus, given the estimated cost of, say, a highway project, one can determine the quantity of energy that will be consumed in its construction by multiplying the cost times the "Btu-per-dollar" factor available from I/O data. The simplicity of this approach, together with the availability of voluminous I/O data has contributed to its popularity.

One drawback of this approach is that I/O data are based on inadequate government statistics, which may require an 8- to 10-year time lag between the actual expenditure and its publication in the I/O system, necessitating the use of inflationary factors, which may vary from one good or service to the other.

The main drawback, however, is that I/O uses the cost of the energy of fuels as an input, and this cost varies considerably from region to region. Electricity costs may be three times higher in one region of the U.S. than in another, but an I/O analysis would not consider the energy used, which is the same regardless of the region, but the dollar cost of that energy, which is significantly different.

Additional Sources

Statistics provide data for actual passengers or freight transported by various systems, allowing estimates of "load factors;" i.e., actual service rendered vs potential service capability of a system.

Direct fuel consumption of vehicles is field- and laboratory-measured under actual or simulated conditions. These values are then used in conjunction with studies of the actual mix of various vehicle sizes and other characteristics to produce direct energy consumption figures for a "composite" vehicle that represents the statistical average of the "fleet on the road."

ENERGY FACTORS

An important part of this study has been the collection and presentation of available energy factors that have been established by the various methods listed in the following. The actual values are presented in Appendix A (the "Energy Factor Handbook"), and brief amplifying remarks, keyed to each of these values, are presented in Appendix B ("Commentary on the Energy Factor Handbook"). Appendix C is a bibliography keyed to the same values as Appendices A and B.

Appendices A and B are intended for users familiar with the subject; therefore, detailed discussion has been omitted from them and is, instead, presented in the following.

Fuels

Transportation consumes a variety of substances as fuels. Approximately 96% of these fuels are derived from petroleum(1). The direct thermal energy inherent in these fuels can be measured in the laboratory. Published values vary by +15% due to the differing chemistry of natural deposits, refining techniques, and precision of laboratory measurements. Indirect energy expended in drilling, transporting, and refining petroleum fuels has not been identified adequately. Estimates suggest its magnitude to be between 10% and 20% of the thermal energy of ready-to-use fuels, and to vary with the type of distillate. Faced with this degree of precision, the authors have opted to report "default" values of petrochemical fuel energy, which are, in fact, estimates of thermal potential that do not, in theory, include indirect energy but may be considered as doing so for practical purposes.

Nonpetroleum-derived fuels are being considered for expanding roles in transportation. Again, the direct thermal energy inherent in these fuels can be measured in the laboratory, but insufficient information is available as to the quantity of indirect energy required to produce and store them. Indications suggest that the indirect energy may be of substantial magnitude. For example hydrogen, a prime candidate for use as a clean, portable fuel of the future, not only requires indirect energy to produce, but storage is a problem: as a pressurized gas in heavy; large containers (which require energy to manufacture); as a supercold liquid (which must constantly leak in order to maintain temperature), or absorbed in special compounds, from which the gas is released upon demand (still at the experimental stage). The indirect energy associated with nonpetroleum fuels has not been identified, thus the values reported herein represent the direct thermal energy only.

TABLE 1.
ENERGY OF SELECTED FUELS

Fuel	Energy per Unit
Ammonia (liquid)	6.25×10^4 Btu/gal
Coal	1.07×10^4 Btu/lb
Ethanol	8.93×10^4 Btu/gal
Hydrogen (liquid)	3.21×10^4 Btu/gal
Natural gas	1.00×10^3 Btu/ft^3
Gasoline	1.25×10^5 Btu/gal
Jet fuel	1.23×10^5 Btu/gal
Oil, diesel	1.39×10^5 Btu/gal
Oil, bunker C	1.54×10^5 Btu/gal
Oil, crude (Calif.)	1.38×10^5 Btu/gal
Wood	8.90×10^3 Btu/lb

Special consideration is due electricity, which is used as fuel. Electricity requires indirect energy input to a power plant in the form of petroleum, natural gas, coal, hydraulic pressure, nuclear reaction, or geothermal taps (wind, wave, and solar power are still experimental). The majority of electric power plants use petroleum and natural gas fuels, and their efficiency when transmission losses are included is 0.33. It is thus important, when discussing electricity, to clarify whether the energy units presented refer to the quantity of electrical energy used by a vehicle or system (reflected in the utility bill) or the equivalent energy consumed to produce this quantity of usable electricity (a figure three times greater). Transportation energy analyses must consider the total energy consumed to provide a given service, thus should use the larger figure.

Materials and Construction

Transportation requires use of manufactured goods for construction and operation of systems. The list of materials is endless, and ranges from aluminum carburetors to concrete structures to dynamite for blasting. None of these materials is found ready-to-use in nature; energy must be expended to refine the raw materials and transport them to the point of use. Some materials or finished products require considerably more energy to produce than others and studies are being conducted to estimate the quantity of this energy. Roadway-related transportation has been the best-explored mode to date. For example, energy values for roadway pavements, presented in Table 2, are based on typical quantities of materials that make up the structural section. The values include the energy required to produce each material (such as aggregates and asphalt), to heat and combine them, and to transport the mix, and, finally, the energy consumed by equipment (such as paversand rollers) to place them and create the final product.

TABLE 2.
ENERGY CONSUMED FOR PAVEMENTS IN-PLACE

Section	Energy per Unit*
Flexible section (AC surface):	
Mainline traffic design	8.05×10^9 Btu/ln-mi
Moderate traffic design	5.84×10^9 Btu/ln-mi
Shoulder 10 ft wide	4.87×10^9 Btu/mi
Rigid section (PCC surface):	
Mainline traffic design	6.72×10^9 Btu/ln-mi
Moderate traffic design	5.77×10^9 Btu/ln-mi

*Includes the thermal energy of the asphalt binder.

Wearout, replacement, and routine maintenance must be considered in an energy analysis, together with realistic "useful lives" of projects. Although it is possible for, say, a concrete bridge to provide service for 100 years, new alignment or widening requirements for a roadway may render the bridge obsolete in 20 years. Maintenance-related data are scarce and require further investigation.

Transportation Modes

Transportation of passengers or cargo is accomplished by various modes, each unique in its energy consumption characteristics. This study addresses all major modes in current use by modern society (except walking, bicycling, or use of pack animals). These modes have been classified into six general types, as follows:

1. Roadway transportation.
2. Rail transportation.
3. Personal rapid transit.
4. Air transportation.
5. Marine transportation.
6. Pipeline transportation.

The energy characteristics of each transportation type are described in the following discussion.

1. Roadway Transportation Modes. - Roadway vehicles include motorcycles, passenger cars, vans, trucks, and buses. Their power plants, with insignificant exceptions, use either gasoline or diesel fuel, the latter usually found only in very heavy-duty trucks and in a great number of large buses. The role of diesel fuel in vehicle power plants is expected to increase in the future, however.

Fuel consumption characteristics vary for each vehicle, but statistical information on sales, registrations, fuel consumption tests, and related information by the Environmental Protection Agency, the Federal Highway Administration, and others, allows postulation of "composite" vehicles by type. These "composite" vehicles represent a statistical average of the actual fleet on the road in terms of their fuel consumption. Detailed data on fuel consumption of composite vehicles are presented in Appendix A. For passenger cars, this "composite" vehicle changes slightly each year, due to older cars being driven less and eventually removed from service, while new, more fuel-efficient cars take to the road. Figure 4 shows the predicted change in the fuel economy of the "composite" private car through the year 2000.

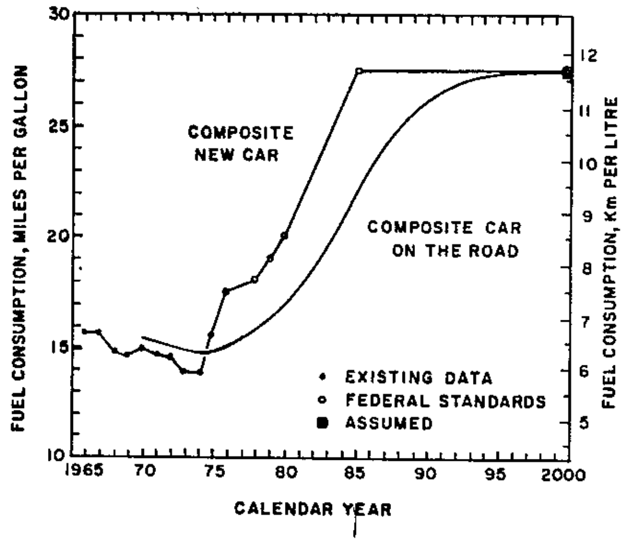

Fig. 4. Fuel consumption rates of composite passenger cars (weighted EPA: 45% rural cycle, 55% urban cycle).

Factors that influence fuel consumption of roadway vehicles may be classified as vehicle-related and facility/traffic-related. Major vehicle-related factors include engine size, fuel type, gross vehicle weight, and speed. Another important factor is the case of "cold starts." Engines and drive trains achieve their best efficiency when warmed to operating temperatures, and thus consume more fuel when cold. Lesser factors under this category include driver behavior, state of engine tune, tire type and pressure, and aerodynamics.

Major facility/traffic-related factors are roadway grade (vertical alignment), because more energy is required to climb than to travel on a level road, and the acceleration/decelerations/idling necessitated by dense traffic and/or traffic signals. Another important factor is the effect of substandard pavements, which extract a fuel penalty due to tire slippage and/or speed changes. Lesser factors include roadway curvature (horizontal alignment), altitude, and meteorological conditions. The last two are usually omitted from an analysis except in special cases (for ice and snow effects see Claffey (10).

From the data available, roadway vehicles were categorized as passenger cars, trucks, and buses. Motorcycles are not included due to insufficient data.

Passenger cars as defined herein include not only sedans, but also other lightweight 2-axle vehicles having a gross vehicle weight (GVW) under 8,000 lb (3,629 kg). Statistics(11) indicate that 99.8% of 2-axle, 4-tire vehicles have a GVW under 8,000 lb. This category includes nearly all pickup trucks and vans(12), which, although having a cargo-carrying potential, in practice are seldom heavily loaded. Fuel used is almost exclusively gasoline(12). Figure 5 shows the fuel consumption of the 1974 composite car at various speeds.

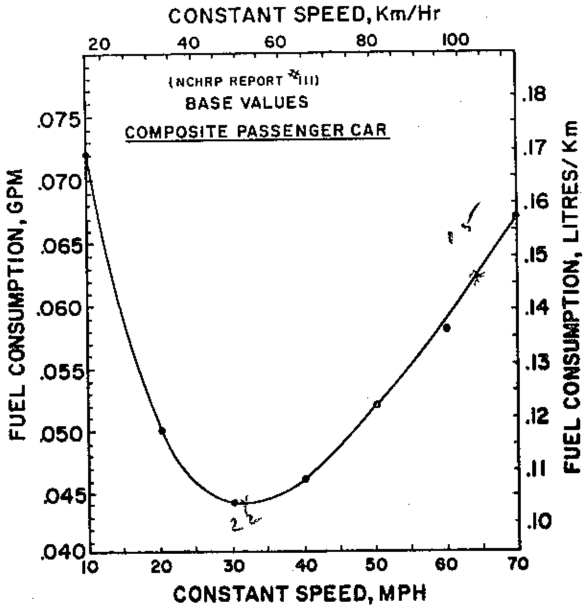

Fig. 5. Fuel consumption of composite passenger car on the road, at constant speeds. (base year = 1974)

Trucks are separated into two major subcategories: Two-axle vehicles having 6 or more tires, and tractor-semitrailer vehicles.

Two-axle, 6-tire vehicles represent light to heavy-duty carriers having a GVW between 8,000 and 16,000 lb (3,629 and 7,257 kg)(13). Statistics indicate that 95.3% of two-axle, 6-tire trucks exceed 10,000 lb (4,536 kg) GVW(11). This category includes a substantial percentage of all dump trucks, tankers, log bunk, transit mix and refrigerator trucks(12). Fuel used is 95% gasoline and 5% diesel(12). Figure 6 shows the fuel consumption of this type of vehicle at various speeds.

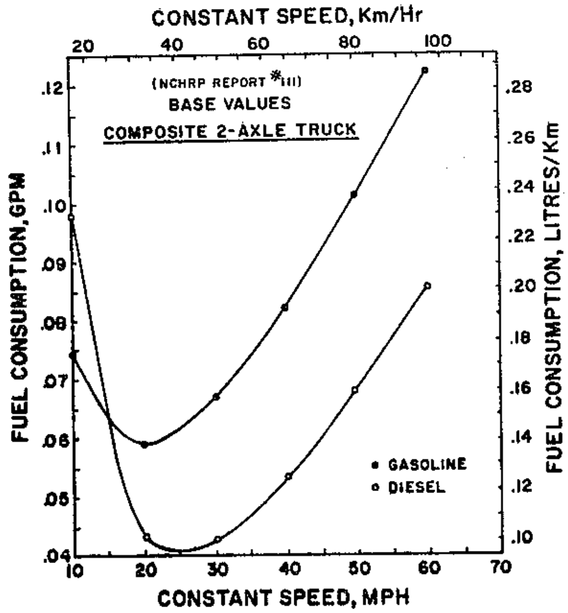

Fig. 6. Fuel consumption of composite 2-axle, 6-tire truck.

Tractor-semitrailer trucks represent heavy-duty multi-axle carriers exceeding 16,000 lb (7,257 kg) GVW. Fuel consumption data are based primarily on vehicles having a GVW between 40,000 and 50,000 lb (18,144 and 22,680 kg)(13). Fuel used is estimated as 65% gasoline, 35% diesel(13). Figure 7 shows the fuel consumption of this type of vehicle at various speeds.

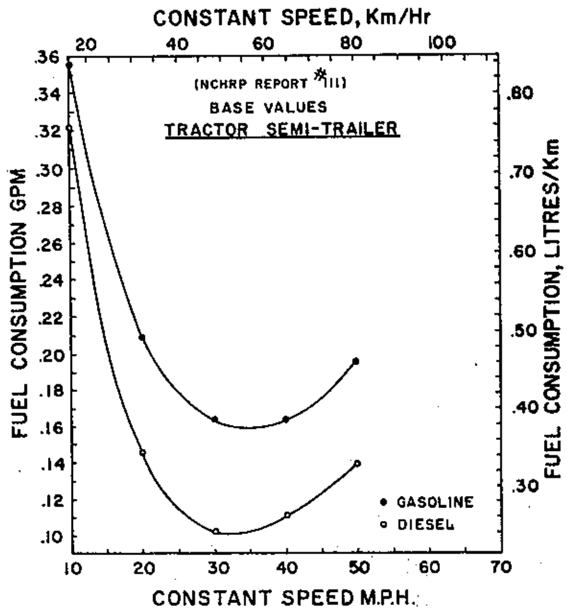

Fig. 7. Fuel consumption of composite tractor-semitrailer truck from 40,000 to 50,000 lb GVW.

Buses provide mass transit service for passengers between cities, within cities, or for school children. Weights and seating capacities vary. Fuels include gasoline, diesel, liquid propane, and electricity. There have been no recent tests of fuel consumption characteristics vs speed and grade for transit buses, previous tests having been made with an obsolescent vehicle(13). A computer model has been developed, describing fuel consumption characteristics vs speed and grade for intercity buses(14). Fleet statistics are available from various sources on the over all fuel consumption rates expected under actual service conditions. City transit bus fuel consumption is affected by the frequency of stops made in the route, and this factor must be considered in an energy analysis when sufficient information is available. Figure 8 gives the fuel consumption vs stop frequency of transit buses.

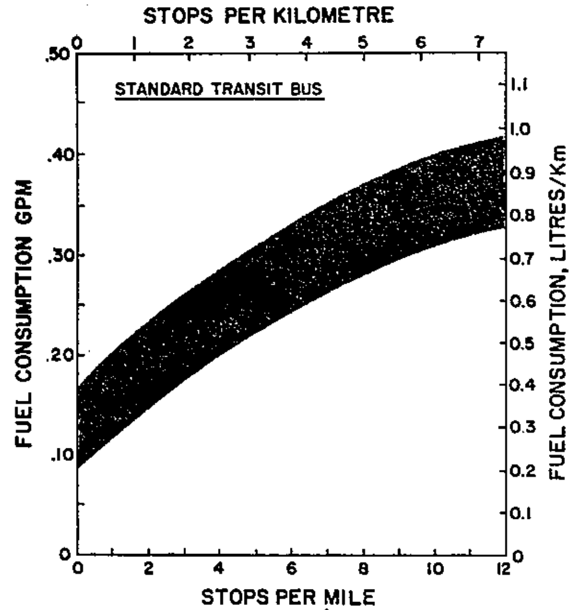

Fig. 8. Diesel fuel consumed vs bus stop frequency.

In general, it is worth commenting that most of the detailed data on fuel consumption vs speed and grade are based on obsolescent vehicles (1964-68 model cars, 1962-65 2-axle trucks, a 1960 tractor-semi-trailer and a 1960 transit bus)(13). Work of a similar nature(80) has been recently conducted on 1970-1974 model cars by the same author, and interested readers are urged to review this lastest study.

The indirect energy consumption associated with roadway vehicles includes vehicle-related and system-related items. Vehicle-related items include the actual wear out and replacement of the vehicle itself, which requires estimates of its service life in terms of miles driven; wear out of component parts such as tires, and routine maintenance and replacement of lubricants. Possible salvage energy may also be considered. System-related items include construction and maintenance of roads, bridges, etc., as well as support facilities such as parking lots, service stations, and garages. Attempts have been made to estimate the energy equivalent of items such as vehicle insurance(15). This is correct in principle, but the energy impact is so small as to have no effect on the precision of the analysis.

Information on indirect energy of vehicles is based on studies of the various materials incorporated within a finished vehicle (i.e., steel sheet, aluminum, copper, rubber, plastics, etc.) the energy required to produce each material, and the energy required to form and assemble the finished product(16,17). This is combined with estimates of the service life(18,19,20), and the energy consumed in routine maintenance(13,21,22).

Information on system-related indirect energy is based on several limited studies of construction materials(23,24,25) and operations(19,26,27), and on maintenance functions. This is combined with estimates of service life and the energy required for other operating requirements of the roadway system, such as illumination, signals, and landscaping. A substantial part of the data presented on roadway construction has been developed by the authors.

2. Rail Transportation Modes. - Fixed rail vehicles are trains and rail mass transit units. In addition, many personal rapid transit (PRT) and group rapid transit (GRT) vehicles operate on rails or special tracks. These are discussed separately.

Trains carry passengers or cargo, seldom both. Their power plants consist primarily of diesel-fueled engines, which run generators to supply electric drive motors (hence their designation: "diesel-electric"). Some trains are powered directly by electricity from either overhead wires or a third rail arrangement. Gas turbines are also used on some routes.

Fuel consumption characteristics vary and are influenced by three major factors: speed, gross weight, and terrain (grades) (28). Additional factors include delays or slowdowns due to the number of trains using a given route and track condition (the number and length of sections requiring slowdowns). In the case of commuter trains, the frequency of stops also becomes an important factor. Inasmuch as trains are designed to serve specific routes, the power plants are designed to meet the specific requirements of the routes. Passenger trains are usually composed of a standard number of units and weigh essentially the same whether empty or full. Thus, given speed and terrain, designers provide the appropriate power plant.

Freight trains vary as to number of units, gross weight, route and speed, so the power must be custom-fitted to each train as it is assembled at the yards. At that point, an estimate of the "gross trailing weight" is made and the appropriate number and size of locomotives is assigned to perform the task. Where required along the route, additional locomotives are temporarily attached to help climb steep grades. Locomotives are rated according to their maximum horsepower and weight is usually expressed in tons (2,000 lb)(29).

The railroad industry has conducted studies to aid in conservation of fuel(29). Through these and other studies (28,30), information as to fuel consumption rates of locomotives has become available, as well as computer models that report fuel consumption of trains over specific routes, at various speeds and various horsepower-to-weight ratios. Table 3, condensed from Appendix A, presents the fuel consumption rate per rated passenger (per seat) of selected trains.

TABLE 3.
DIESEL FUEL CONSUMPTION OF SELECTED TRAINS

Route	Distance (mi)	Propulsion Type	Fuel Consumed (gal/seat-mi)
Seattle-Havre	903	Diesel-elec.	0.009
Atlanta-Wash.	633	Diesel-elec.	0.012
New York-Wash.	284	Gas turbine	0.010
Chicago-St. Louis	277	Electric	0.013*

*Equivalent diesel fuel.

Studies also reported on various rail mass transit systems provide information as to their fuel consumption characteristics, the rated passenger capacity, speed, and weight(5,18,28,29,30,31,46,64,84). Table 4, condensed from Appendix A, presents the characteristics of selected rail mass transit systems.

TABLE 4.
CHARACTERISTICS AND ENERGY CONSUMPTION OF SELECTED MASS TRANSIT SYSTEMS

System	Seats [Standing] per car	Rated (hp/seat)	Wt/seat (Tons)	Energy Consumed (Btu/seat-mi)
Lindenwold	84	7.6	0.39	N.A.
Toronto	83 [N.A.]	1.9	0.35	860
San Francisco	72 [72]	7.4	0.40	850
Philadelphia	56 [N.A.]	5.8	0.43	1075
Cleveland	54 [N.A.]	3.4	0.51	686
Chicago	51 [N.A.]	3.4	0.41	952
New York	47 [N.A.]	7.3	0.84	1208

Estimates have been made of the indirect energy required for vehicle(16) and guideway construction(17,19). However, the energy requirements for operation and maintenance facilities have not been adequately identified.

3. Personal and Group Rapid Transit Modes. - Personal and group rapid transit systems are usually included under the labels "PRT" and "GRT," respectively. These transportation systems are in a state of research and development, and each operational system is unique in concept and design. The common features of existing operational systems are as follows: